AD-A132 351 NUMERICAL MODELING OF THE MOSBJT(U) HAWAII UNIV AT MANOA HONOLULU DEPT OF ELECTRICAL ENGINEERING D OKADA ET AL. JUL 83 N00014-76-C-1081 1/1

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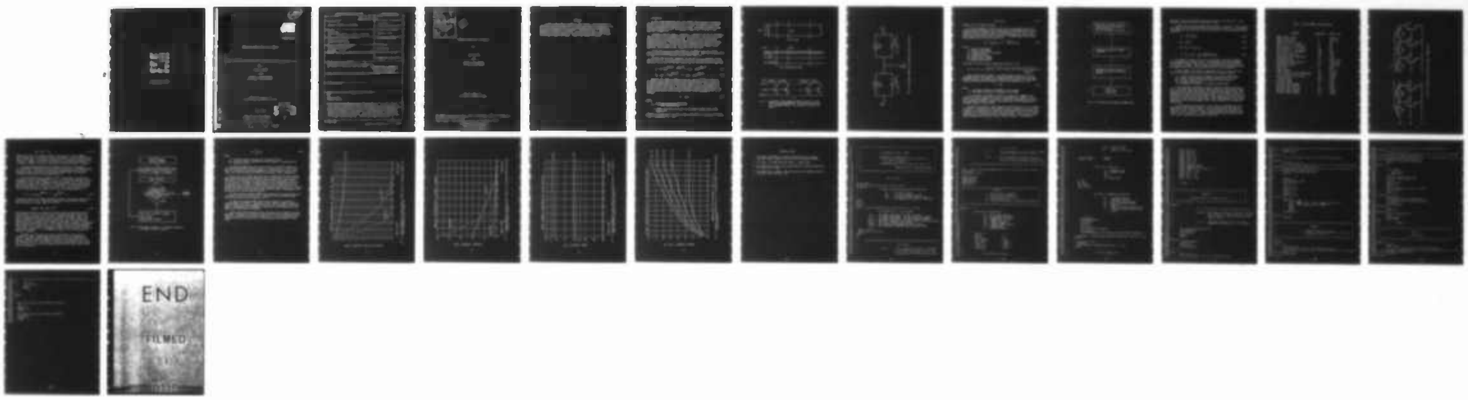

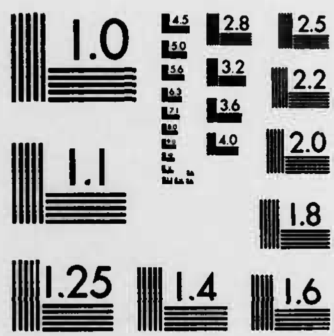

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NUMERICAL MODELING OF THE MOSBJT

by

David Okada

and

James W. Holm-Kennedy
Principal Investigator

ONR Final Report II
Contract No. N-0014-76-C-1081

July 1983

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A132 351	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Numerical Modeling of the MOSBJT		5. TYPE OF REPORT & PERIOD COVERED Final Report II
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) David Okada James W. Holm-Kennedy, Principal Investigator		8. CONTRACT OR GRANT NUMBER(s) N00014-76-C-1081
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Hawaii Honolulu, Hawaii 96822		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Arlington, Virginia Code 427		12. REPORT DATE
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

MOS
BJT
Merged Devices
High Gain Devices

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A totally merged MOSFET and BJT has been proposed. The device exhibits complicated-non-linear characteristics under certain operating conditions. Due to the distributed character of this novel merged device, a straightforward lumped device approach is not adequate. A distributed model is proposed and analyzed using numerical techniques. The active device area is shown to be affected by bias and contributes to the non-linear character of the characteristics under suitable conditions. Several gate shapes are treated.

NUMERICAL MODELING OF THE MOSBJT*

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*The MOSBJT was proposed by Prof. James W. Holm-Kennedy, Electrical Engineering Department, University of Hawaii.

Patent pending. Work supported in part by the University of Hawaii.

ABSTRACT

A totally merged MOSFET and BJT has been proposed. The device exhibits complicated non-linear characteristics under certain operating conditions. Due to the distributed character of this novel merged device, a straightforward lumped device approach is not adequate. A distributed model is proposed and analyzed using numerical techniques. The active device area is shown to be affected by bias and contributes to the non-linear character of the characteristics under suitable conditions. Several gate shapes are treated.

1. Introduction

A novel merged MOSFET/BJT device (the MOSBJT) was previously described [1]. The device is fully merged which results in a distributed behavior. The MOSFET channel can be used as an emitter or as a collector. In order to analyze the device, a distributed FET BJT model must be used. Approximate analytical models have been treated [2] and will be reported elsewhere and is similar to that described in Report III.

The MOSBJT numerical model is based upon an equivalent circuit for the MOSBJT. The construction of the equivalent circuit is as follows: First the distributed bipolar injection into the MOSBJT channel is modeled by dividing the device length-wise into many equal sections (refer to Fig. 3.1a, b). Each section is then represented by a n-channel metal oxide semiconductor field effect transistor (MOSFET) connected to a npn bipolar junction transistor (BJT) resulting in the equivalent circuit shown in Fig. 3.1c. Built into this circuit model is the assumption that minority carrier transport occurs vertically.

The npn BJTs and the n-channel MOSFETs in the MOSBJT equivalent circuit (Fig. 3.1c) are represented by their classical DC models. These are the Ebers-Moll BJT model [3] and the distributed analysis MOSFET model [4].

The Ebers-Moll BJT model represents the npn BJT with the equivalent circuit shown in Fig. 3.2. From the equivalent circuit the following expressions for the collector current (I_C') and the base current (I_B') for the transistor are determined.

$$I_C' = \alpha_F I_{ES}[e^{qV_{BE}/KT} - e^{qV_{BC}/KT}] - I_{CS}(1 - \alpha_R)[e^{qV_{BC}/KT} - 1] \tag{3.1}$$

$$I_B' = I_{ES}(1 - \alpha_F)[e^{qV_{BE}/KT} - 1] + I_{CS}(1 - \alpha_R)[e^{qV_{BC}/KT} - 1] \tag{3.2}$$

The Ebers-Moll model parameters ($\alpha_F, \alpha_R, I_{ES}, I_{CS}$) for the BJT elements in the MOSBJT circuit model are extracted from the experimental data of a typical rectangular MOSBJT operating with the entire channel active. The magnitude of the BJT collector current for a particular section (I_{Cx}) is proportional to the collector area of that section. The proportionality constant is determined by normalizing the area of each section to the total collector (channel) area. This factor is then used to scale the total collector current expressed by Eq. (3.1) yielding:

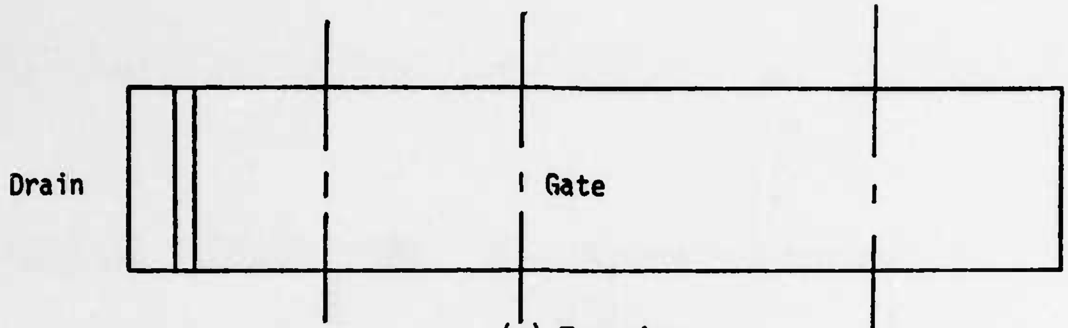
$$I_{Cx} = K_x I_C' \tag{3.3}$$

where

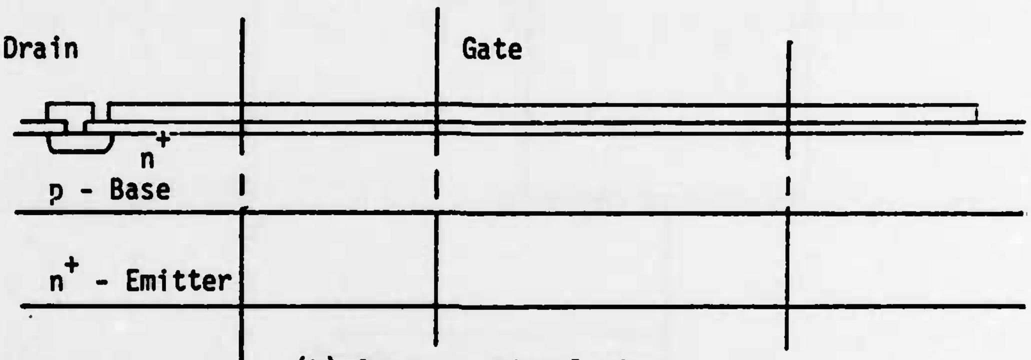
$$K_x \equiv \frac{\text{collector area of the } x^{th} \text{ section}}{\text{total collector area}}$$

$x \equiv$ integer specifying the section of the numerical MOSBJT model being referred to

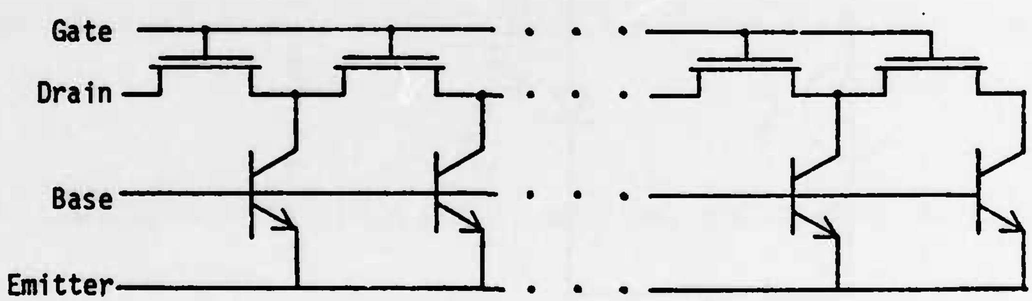
Similarly an expression for the base current contribution of a particular section, x can be expressed by Eq. (3.4).



(a) Top view



(b) Cross-sectional view



(c)

Fig. 3.1 Development of the MOSBJT equivalent circuit. (a) Top view of a rectangular MOSBJT. (b) Cross-sectional view of a rectangular MOSBJT. (c) Equivalent circuit of the MOSBJT.

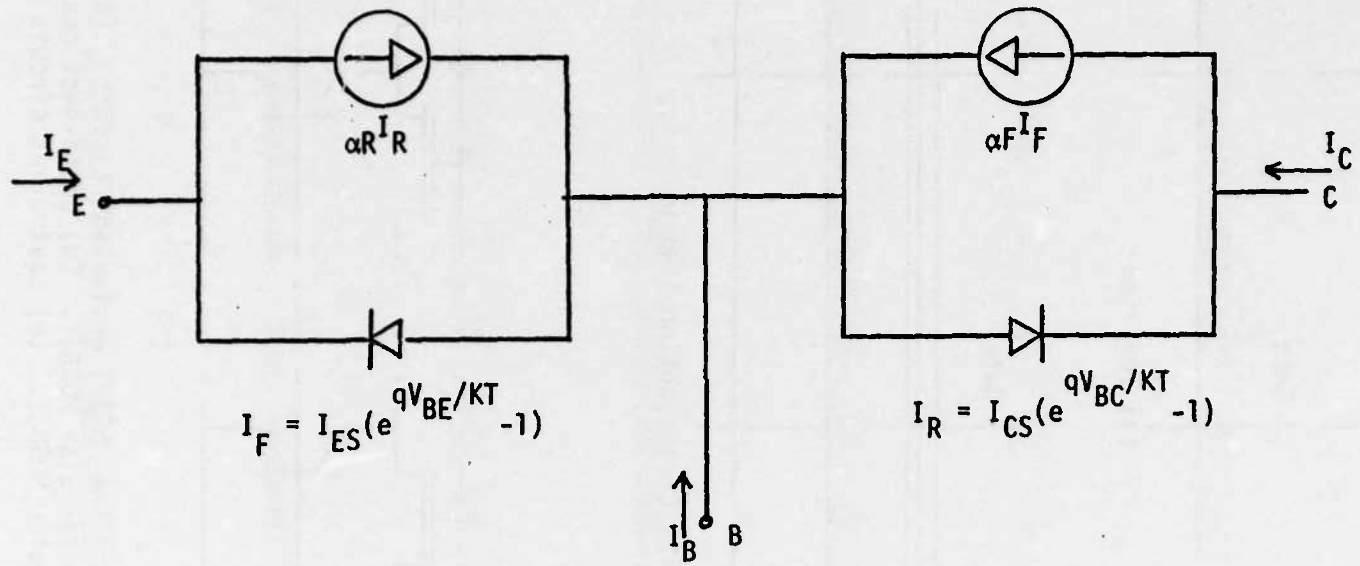


Fig. 3.2 Ebers-Moll model of a npn bipolar junction transistor

$$I_{Bx} = K_x I_B' \tag{3.4}$$

where K_x and x are defined as above.

The n-channel MOSFETs are modeled with the distributed MOSFET model and the gradual channel approximation [3]. Incorporated into the MOSFET model are the assumptions that the channel voltage can be approximated by a half of the sum of the source and drain voltages ($\frac{1}{2}(V_S + V_D)$) and that the channel length is much greater than the depletion region at the drain. The MOSFET model yields the following expression for the drain current (I_D).

$$I_D = \mu_n \frac{W}{L} C_{ox}'(V_G - V_T - (\frac{V_D - V_S}{2}))(V_D - V_S) \tag{3.5}$$

where

- $W \equiv$ width of the channel
- $L \equiv$ length of the channel
- $\mu_n \equiv$ electron mobility in the channel
- $V_T \equiv$ threshold voltage .
- $V_D \equiv$ applied drain voltage
- $V_S \equiv$ applied source voltage
- $V_G \equiv$ applied gate voltage

Solving Eq. (3.5) for the drain voltage (V_D) yields Eq. (3.6).

$$V_D = V_S + V_G - V_T - \sqrt{(V_S + V_G - V_T)^2 - (2(V_G - V_T) + V_S^2 + \frac{2(V_G - V_T)I_D L}{\mu_n W C_{ox}'}} \tag{3.6}$$

The n-channel MOSFET elements in the MOSBJT circuit model (Fig. 3.1c) are represented by Eqs. (3.5) and (3.6). Since each MOSFET represents a section of the MOSBJT channel, the length of each MOSFET should be equal to the total MOSBJT channel length divided by the number of sections as expressed by Eq. (3.7).

$$L' = L/N \tag{3.7}$$

where

- $L' \equiv$ the channel length for the MOSFET circuit elements
- $N \equiv$ the number of sections in the MOSBJT circuit model

For a rectangular gate MOSBJT the width of the gate of the MOSFET circuit element will simply be equal to the width of the MOSBJT gate. MOSBJT's with non-rectangular gate geometries are easily simulated by representing each section with a rectangular MOSFET of length L/N and width equal to the average width of the MOSBJT channel in that section.

The computer algorithm, listed in Appendix A and outlined in Fig. 3.3, consists of 4 modules. The function of these modules, labeled A through D, are as follows: In Module A, the MOSBJT material properties, device characteristics, geometry, and operating bias are defined and various required parameters calculated. The purpose of module B is to determine the extent of channel cut-off. Next in module C the spatial dependence of voltage and current along the channel is determined and

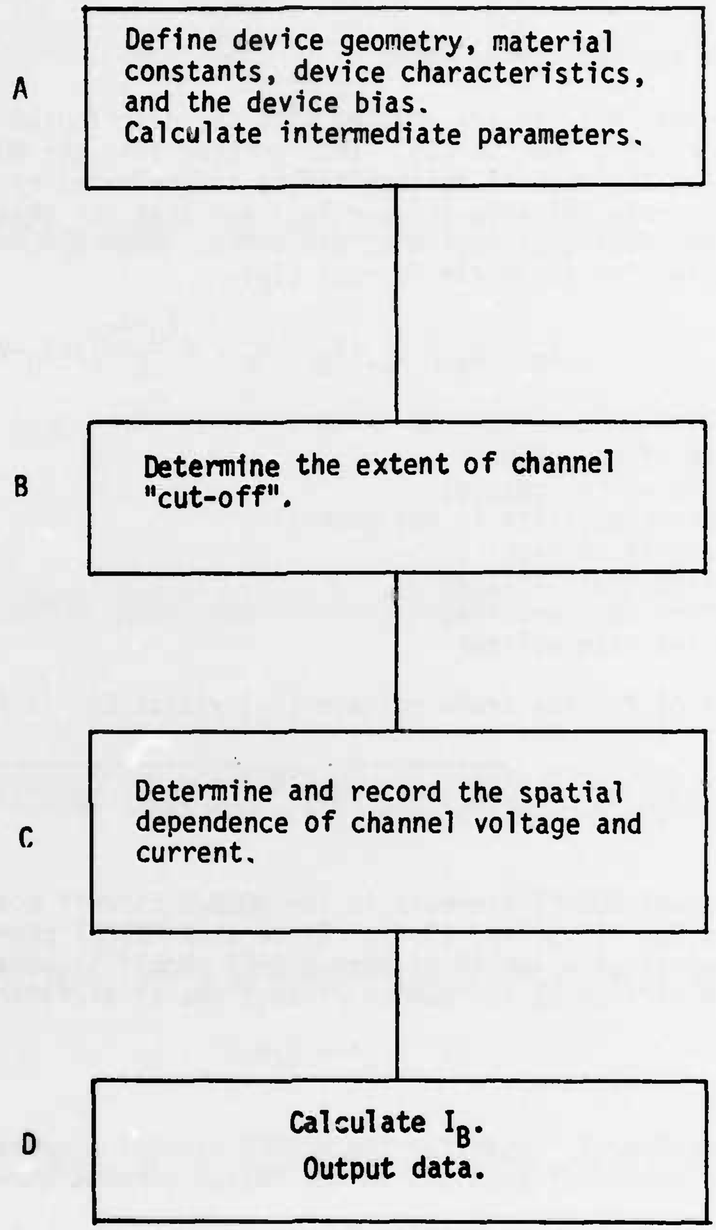


Fig. 3.3 Flow chart of the numerical MOSBJT model

recorded. Finally in module D the base current (I_B) is calculated and its value along with the rest of the data is printed or plotted.

In module A, the numerical MOSBJT model parameters are defined. These parameters are listed in Table 3.1 along with their typical values. Values for ϕ_p, C'_{ox}, V_{FB}, V_T are determined by evaluating the following expressions derived from conventional MOS theory [3].

$$\phi_p = -\frac{KT}{q}\ln(N_a/N_i) \tag{3.8}$$

$$C'_{ox} = \varepsilon_{ox}/T_{ox} \tag{3.9}$$

$$V_{FB} = \phi_M - \phi_S - Q_{ss}/C'_{ox} \tag{3.10}$$

$$V_T = V_{fb} + 2|\phi_p| + \frac{1}{C'_{ox}}\sqrt{2\varepsilon_{sq}N_a(2|\phi_p|-V_{BE})} \tag{3.11}$$

A substantial portion of the iterative algorithm of the numerical MOSBJT model is contained in modules B and C. In these modules the spatial dependence of the MOSBJT's channel voltage and current are determined for a given device bias (V_{DE}, V_{BE}, and V_G). Once the channel voltage and current profiles are known the terminal drain current (I_D) and base current (I_B) can be determined.

The basic MOSBJT circuit model is shown again in Fig. 3.4 with the various nodes, node voltages, and currents labeled with the following notation:

$X \equiv$ integer indicating the X^{th} section of the numerical MOSBJT model
$I_{MX} \equiv$ current flowing through the MOSFET located in the X^{th} section
$I_{CX} \equiv$ collector current for the BJT located in the X^{th} section
$V_X \equiv$ voltage at the X^{th} node
$N \equiv$ the number of sections for the numerical MOSBJT model

A simple approach to determine the node voltages and currents would be to start at the drain where the voltage is known and then calculate the node voltage and current moving from node to node in the direction away from the drain. This approach does not yield a solution because finding V_N (the voltage at the node adjacent to the drain) requires that I_{MN} be known. I_{MN} is equal to the sum of the BJT collector currents at all other nodes. These collector currents are in turn dependent on their respective node voltages. The interdependence of node voltages and currents lead to the development of an iterative approach for the numerical MOSBJT model.

In this approach an initial guess is first made of the voltage (V_1) at the node furthest from the drain (node 1). Next, I_C, can be solved for using the expression for the collector current of a BJT obtained from the Ebers-Moll BJT model (Eq. (3.3)). The current flowing through the MOSFET interconnecting nodes 1 and 2, (I_M) is equal to I_{C1}. A general expression relating the node currents, (Eq. (3.12)) is derived with Kirchoff's current law.

Table 3.1 Typical MOSBJT Device Parameters

Parameter	Nomenclature	Typical Value
MOSBJT channel length	L	3.68E-3 M
MOSBJT channel width	W	2.96E-3 M
Number of sections in model	N	100
Gate voltage w.r.t. the emitter	V_G	30V
Drain voltage w.r.t. the emitter	V_{DE}	20V
Base voltage w.r.t. the emitter	V_{BE}	0.38V
Metal work function (Al)	ϕ_M	4.1ev
Semiconductor work function (Si)	ϕ_S	4.9ev
Oxide permittivity	ε_{ox}	3.45E-11 F/M
Semiconductor permittivity (Si)	ε_S	1.04E-10 F/M
Semiconductor doping	N_a	1.5E16 cm^{-3}
Temperature	T	300°K
Oxide thickness	T_{ox}	1.2E-7 M
Electric potential of the semiconductor	ϕ_p	-0.358V.
Oxide capacitance per unit area	C'_{ox}	2.88E-4 F
Flatband voltage	V_{FB}	-1.08V
Threshold voltage	V_T	1.72V
Ebers-Moll model parameter	α_F	0.9615
Ebers-Moll model parameter	α_R	0.9975
Ebers-Moll model parameter	I_{ES}	1.04E-8
Ebers-Moll model parameter	I_{CS}	1.002E-8

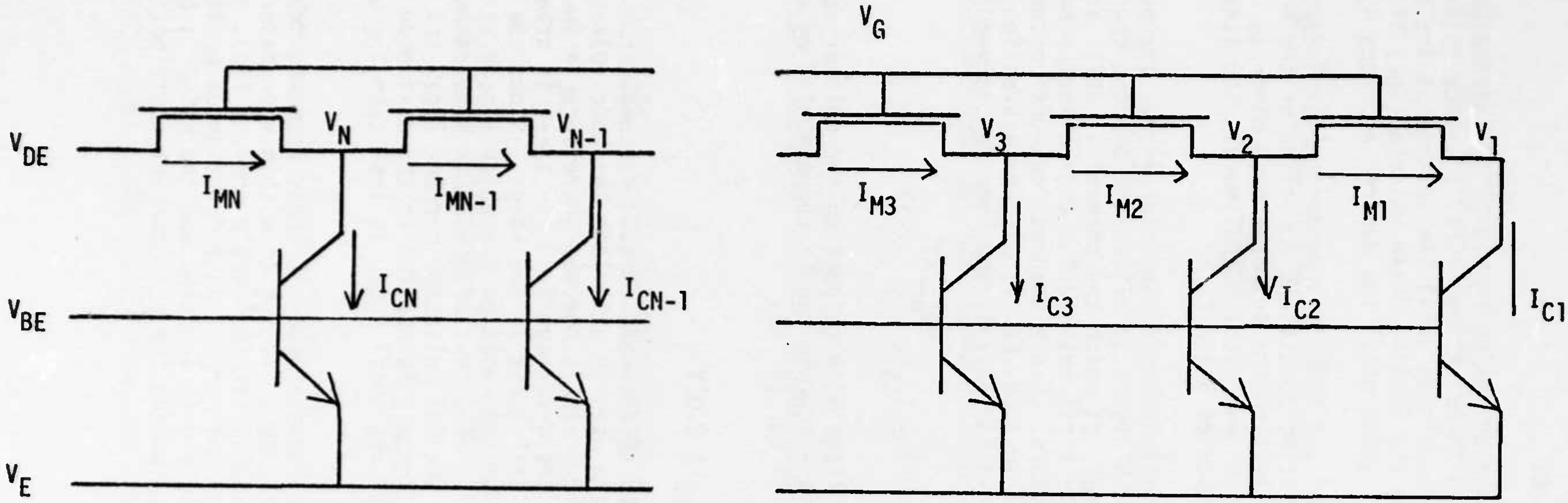


Fig. 3.4 Equivalent circuit for the numerical MOSBJT model

$$I_{MX} = I_{MX-1} + I_{CX} \tag{3.12}$$

Knowing V_1 and I_M, V_2 is then calculated, using Eq. (3.6) in which a MOSFET's drain voltage (V_{X+1}) is expressed in terms of the MOSFET's source voltage (V_X) and drain current (I_{MX}). This process continues until the voltage at the drain (V_{DCAL}) is found. If V_{DCAL} is not equal to the applied drain voltage (V_{DE}) iterative adjustments are made to the initial guess until the desired accuracy is achieved.

From the basic understanding of the MOSBJT's operation [Final Report I] it is known that under certain operating conditions a portion of the MOSBJT channel may be "cut-off" - incapable of collecting the injected base minority carriers. To incorporate channel "cut-off" into the numerical MOSBJT model, the iterative algorithm is partitioned into two modules B and C.

In module B the extent of channel "cut-off" is determined. The algorithm contained in module B is diagramed in Fig. 3.5. First the minimum channel voltage with respect to the emitter (V_{CHEMIN}), at which the channel is still active as a collector is found. This is done by first solving for the collector-base voltage (V'_{BC}) at which channel "cut-off" occurs. Since channel "cut-off" occurs when the BJT collector current (I_{CX}) is equal to zero, Eq. (3.3), the expression for I_{CX} can be set equal to zero, as shown in Eq. (3.13), and then V'_{BC} solved for.

$$0 = I_{CX} = K_X\, {}_F I_{ES}(e^{qV_{BE}/KT} - 1) - I_{CS}(e^{qV'_{BC}/KT} - 1) \tag{3.13}$$

The sum $V'_{BC} + V_{BE}$ is the channel voltage with respect to the emitter necessary for channel "cut-off" to occur. Therefore V_{CHEMIN} can be approximated by adding a small voltage to this sum as shown in Eq. (3.14).

$$V_{CHEMIN} = V'_{BC} + V_{BE} + 0.01V \tag{3.14}$$

After V_{CHEMIN} is found it is applied to the node located furthest from the drain. Equation (3.3), (3.6), and (3.12) are used to calculate the node voltages and currents along the channel until the drain is reached where $V_{DCAL} = V_{N+1}$. Then V_{DCAL} is compared with the applied drain voltage V_{DE}. If V_{DCAL} is greater than V_{DE} the implication is that the initial guess is too large. Since the voltage applied to node 1 was V_{CHEMIN} (the minimum voltage for which a node will be "active"), node 1 must be biased into "cut-off." The "cut-off" node is modeled by setting the node voltage (V_1) to ($V_{BC}+V_{BE}$) and the BJT collector current (I_{C1}) and the MOSFET current (I_{M1}) equal to zero. Then V_{CHEMIN} is applied to the next node (node 2) and the process is repeated. This continues until V_{DCAL} is less than V_{DE} upon which module C is executed.

In module C the voltage at the "active" node furthest from the drain is adjusted until V_{DCAL} is approximately equal to V_{DE} to within a predetermined accuracy. When this occurs the MOSBJT's terminal drain current (I_D), given by I_{MN} and the MOSBJT's channel voltage and current as a function of position along the channel are recorded. Next module D is executed and the MOSBJT's base current (I_B) is calculated. I_B is found by summing the base current contributions of each section as shown below.

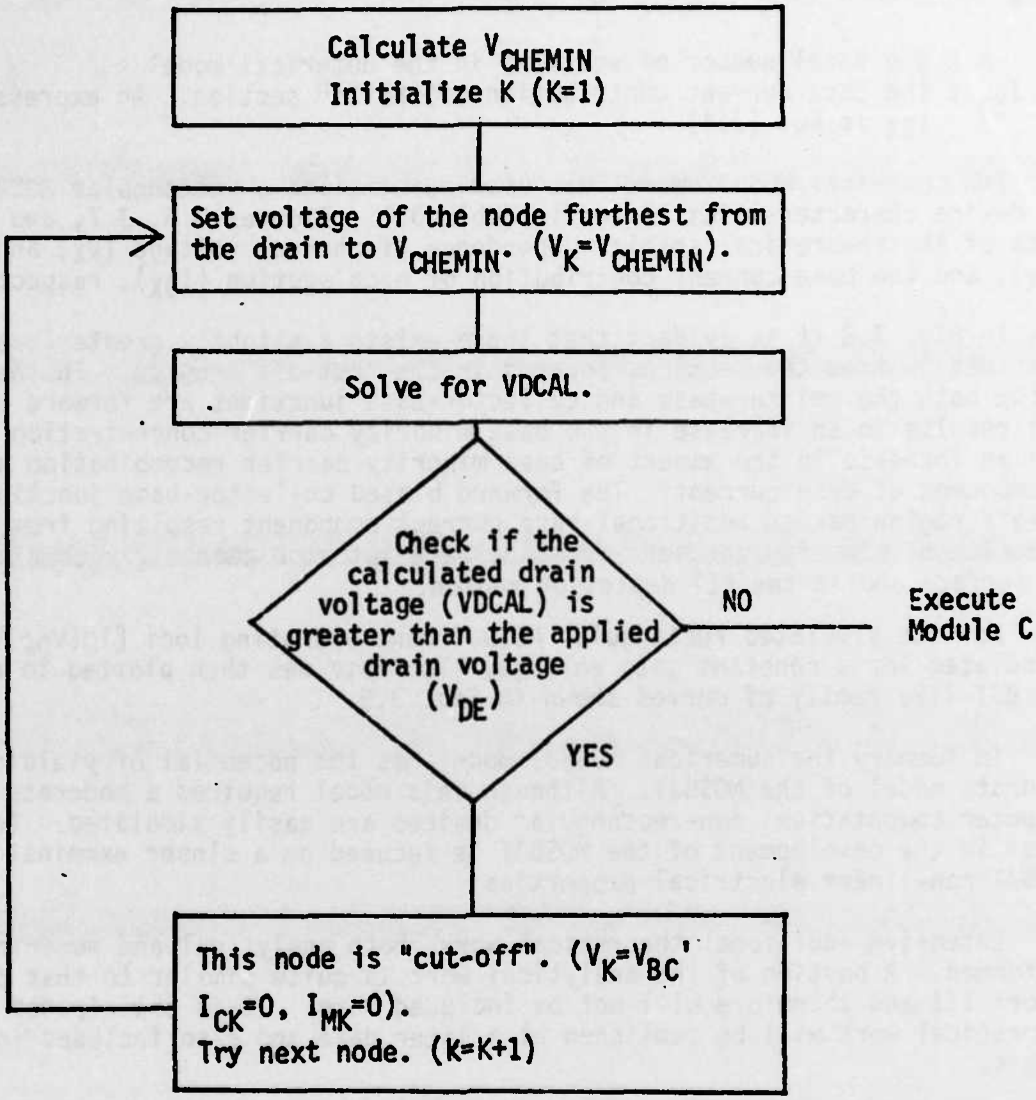


Fig. 3.5 Flow chart of module B. This module determines the extent of channel "cut-off".

$$I_B = \sum_{X=1}^{N} I_{BX} \tag{3.15}$$

where

$N \equiv$ the total number of sections in the numerical model

$I_{BX} \equiv$ the base current contribution of the X^{th} section. An expression for I_{BX} is Eq. (3.4).

The numerical MOSBJT model was used to simulate a rectangular MOSBJT with the device characteristics listed in Table 3.1. Figures 3.6, 3.7, and 3.8 are plots of the theoretical spatial dependence of channel voltage (V_X) and current (I_{MX}), and the base current contribution of each section (I_{BX}), respectively.

In Fig. 3.8 it is evident that there exists a slightly greater base current contribution from the sections located in the "cut-off" region. In the "cut-off" region both the emitter-base and collector-base junctions are forward biased. This results in an increase in the base minority carrier concentration and therefore an increase in the amount of base minority carrier recombination which is a component of base current. The forward biased collector-base junction of the cut-off region has an additional base current component resulting from the "reverse" injection of minority carriers from the base into the channel, recombination at the MOS surface and in the FET depletion region.

For the simulated rectangular MOSBJT many operating loci $[I_D(V_{DE},V_G,I_B)]$ were calculated for a constant gate voltage. The data was then plotted to produce the BJT-like family of curves shown in Fig. 3.9.

In summary the numerical MOSBJT model has the potential of yielding an accurate model of the MOSBJT. Although this model requires a moderate amount of computer computation, non-rectangular devices are easily simulated. The current level in the development of the MOSBJT is focused on a closer examination of the MOSBJT non-linear electrical properties.

Extensive additional theoretical work, both analytical and numerical has been performed. A portion of the analytical work is quite similar to that described in Report III and therefore will not be included here. It is anticipated that this theoretical work will be published at a later date and also included in a Ph.D. Thesis.

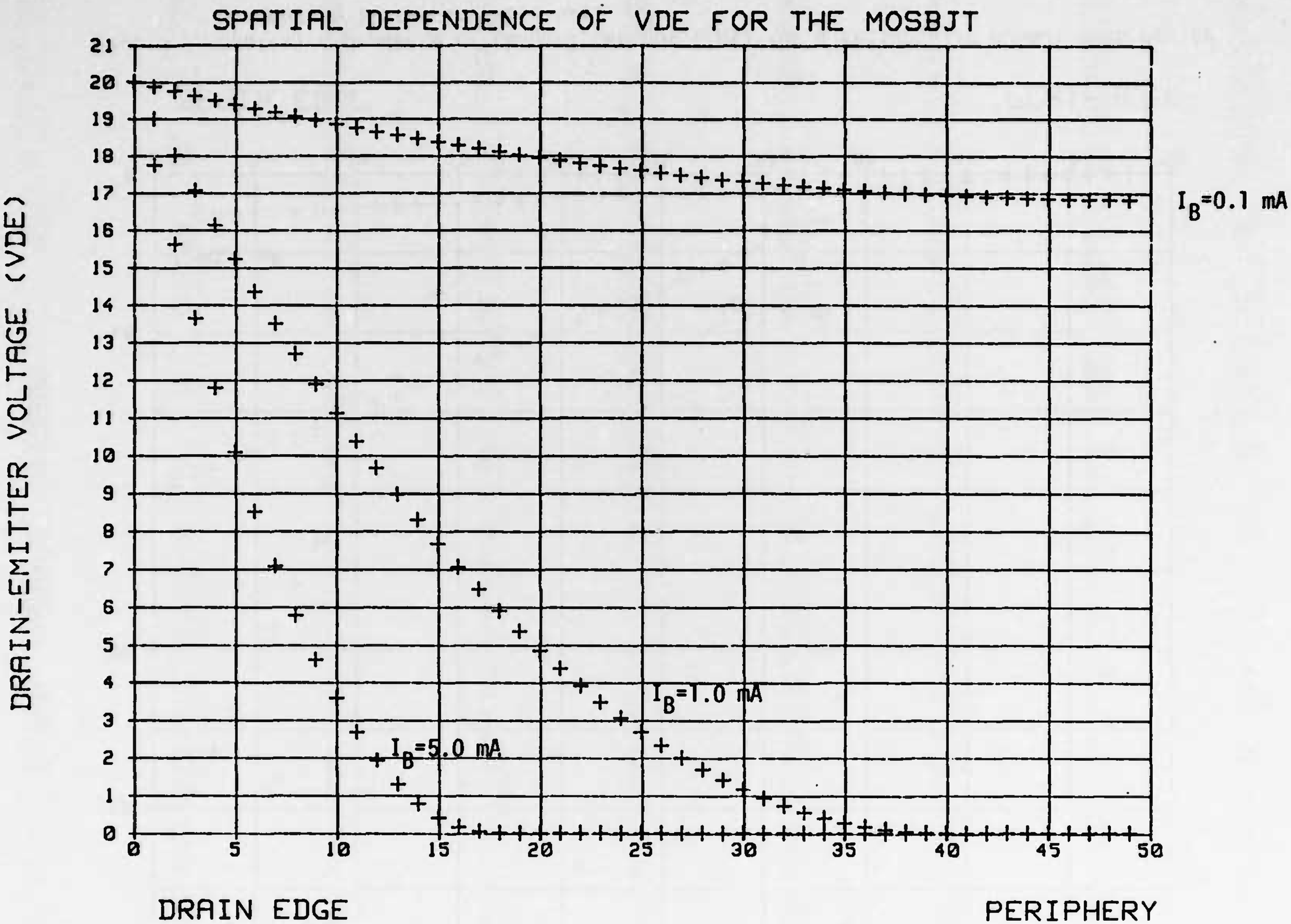


Fig. 3.6 Spatial dependence of channel-emitter voltage (V_X) for a rectangular MOSBJT with device parameters listed in Tabel 3.1.

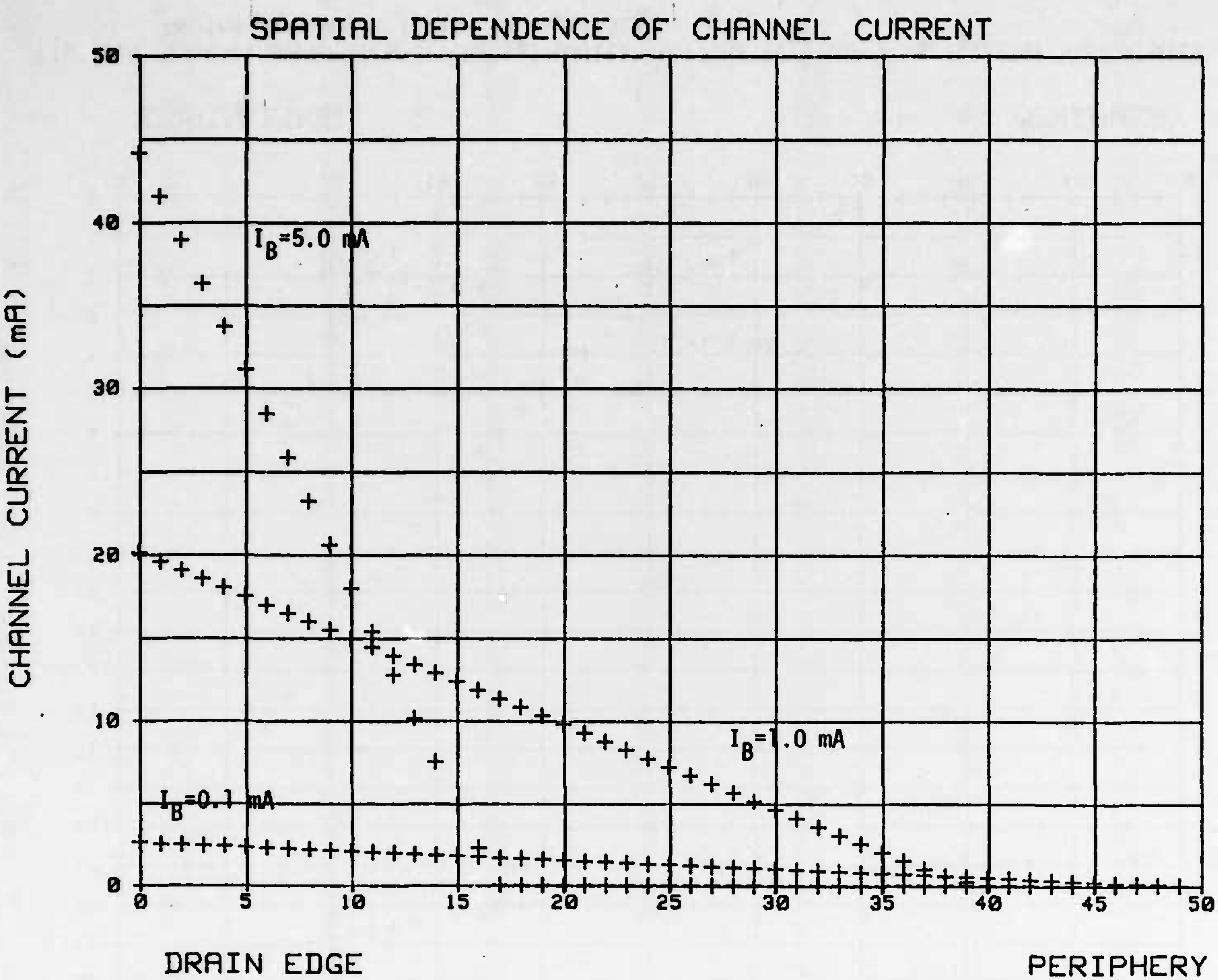


Fig. 3.7 Spatial dependence of channel current (I_{MX}) for a rectangular MOSBJT with device parameters listed in Table 3.1.

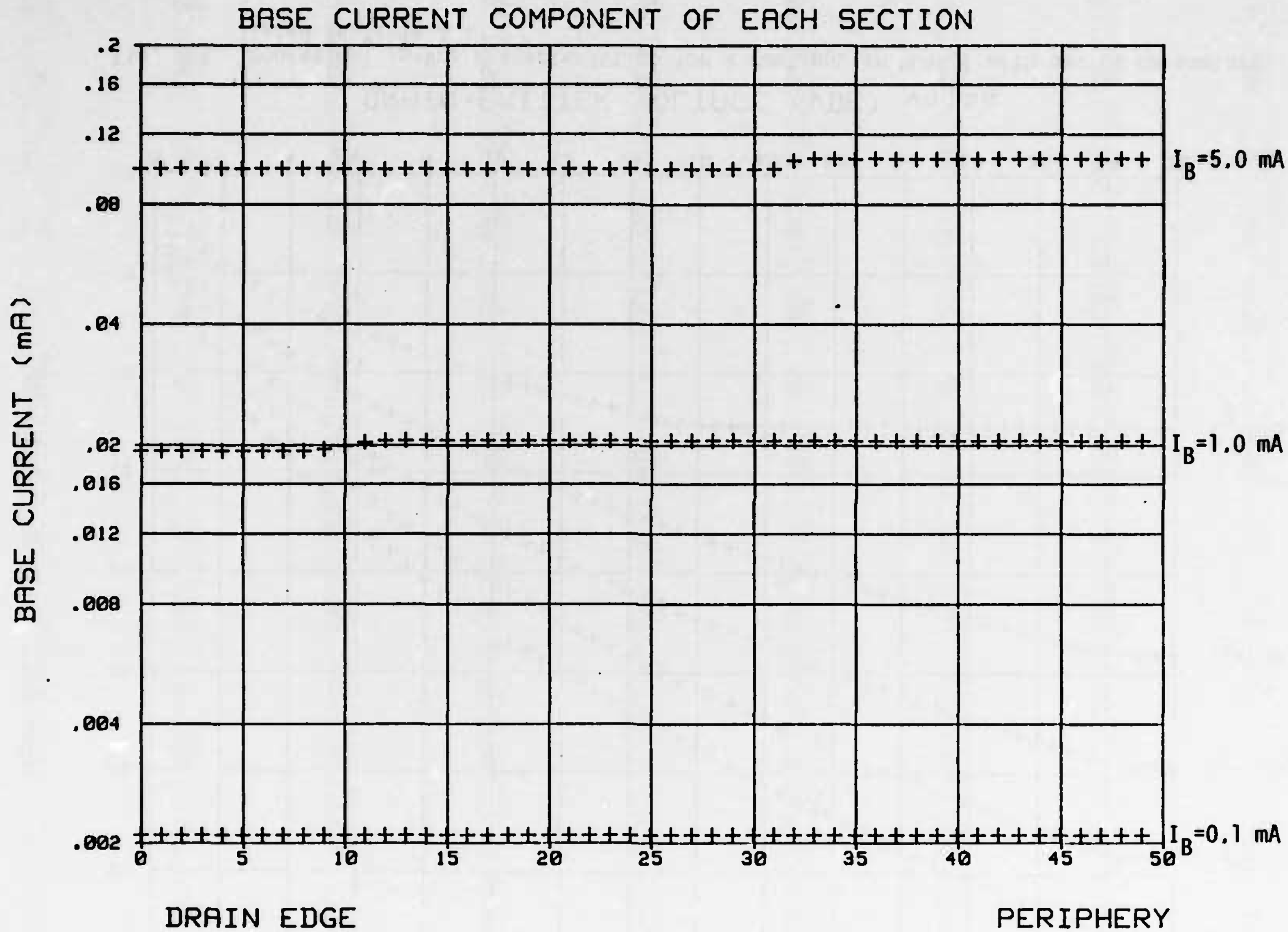


Fig. 3.8 Spatial dependence of the sectional base current contribution for a rectangular MOSBJT with device parameters listed in Table 3.1.

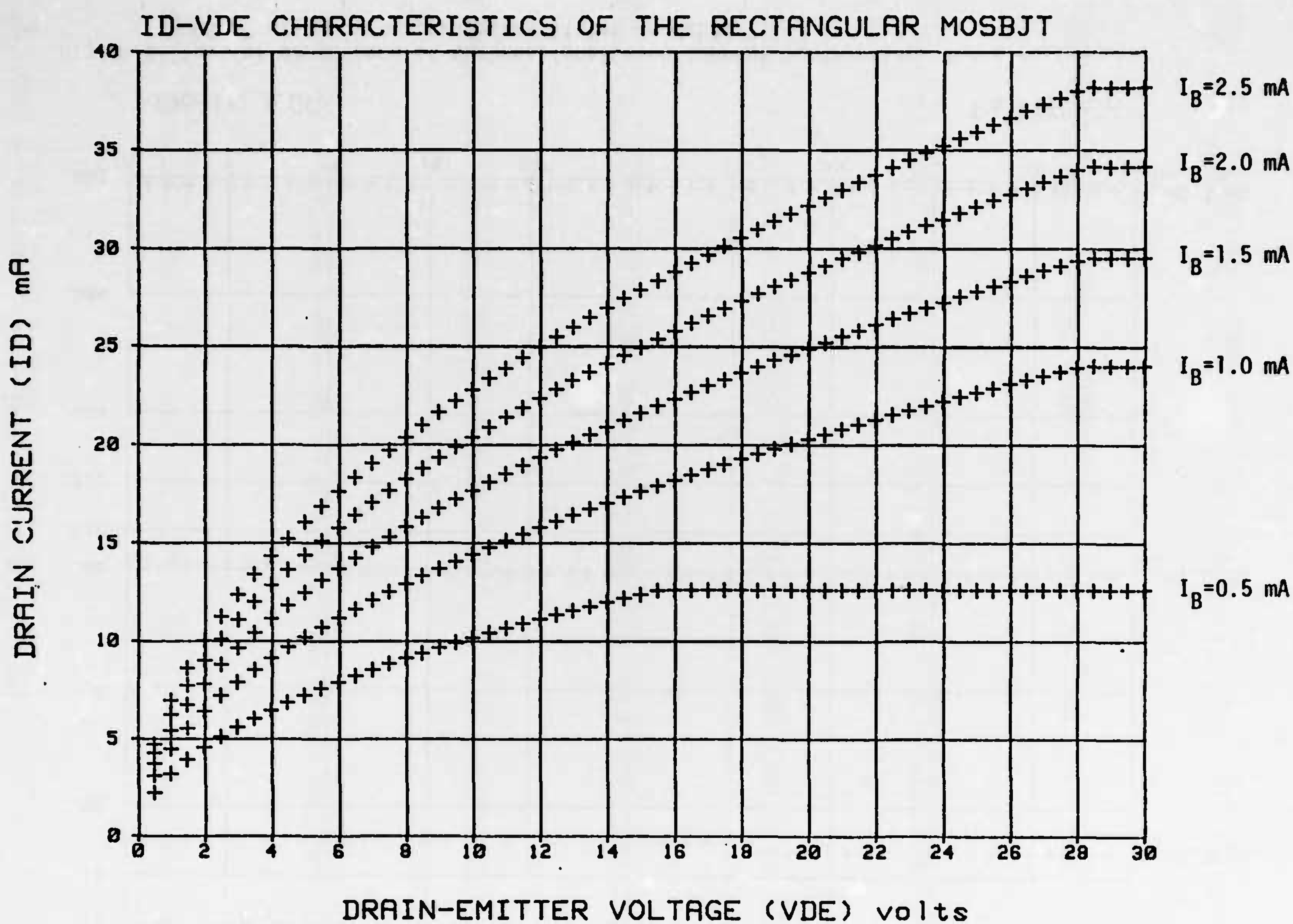


Fig. 3.9 Theoretical I_D-V_{DE} characteristics for a rectangular MOSBJT with device parameters listed in Table 3.1.

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```
10    !
20    !  ****************************************************************
30    !  *                                                              *
40    !  *                                                              *
50    !  *                   THE NUMERICAL MOSBJT^ MODEL                *
60    !  *                                                              *
70    !  *                   Developed by: David Okada                  *
80    !  *                   Research on the MOSBJT is being directed by *
81    !  *                      Dr. James Holm-Kennedy                  *
90    !  *                      University of Hawaii                    *
100   !  *                   Program developed on a HP 9836 with Basic 2.0 *
110   !  *                                                              *
120   !  *                              ^ INVENTED BY DR. JAMES HOLM-KENNDY *
130   !  *                                                              *
140   !  ****************************************************************
150   !
160   !
170   !
180   !                             Main Program
190   !
200   !
210   OPTION BASE 0
220   DIM Ic(200),Im(200),Vd(200),Vs(100),Ibi(200)
230   INTEGER N
240   !                     THE MOSBJT OPERATING BIAS MUST BE SPECIFIED
250   !
260   !                          Vg ...  THE GATE VOLTAGE
270   !                          Vde ..  THE APPLIED DRAIN VOLTAGE
280   !                          Vbe ..  THE EMITTER-BASE JUNCTION BIAS
290   !                          N   ...  THE NUMBER OF SECTIONS IN THE MODEL
300   Vg=20
310   Vde=10
320   Vbe=.40
330   N=100
340   CALL I_v_char(Vg,Vde,Vbe,N,Ic(*),Im(*),Vd(*),Ibi(*),Ibcal)
350   !
360   !                     THE SUBROUTINE I_v_char RETURNS
370   !
380   !          Vd(*) .. THE ARRAY CONTAINING THE NODE VOLTAGES
390   !          Ic(*) .. THE ARRAY CONTAINING  THE BJT COLLECTOR CURRENTS
400   !          Im(*) .. THE ARRAY CONTAINING  THE MOSFET DRAIN CURRENTS
410   !          Ibi(*).. THE ARRAY CONTAINING THE BASE CURRENT FOR EACH SECTION
420   !          Ibcal .. THE TOTAL TERMINAL BASE CURRENT
430   !          Im(N) .. THE TERMINAL DRAIN CURRENT FOR THE MOSBJT
431   !          Vd(N+1). THE CALCULATED TERMINAL DRAIN VOLTAGE (VDCAL)
440   !
450     FOR L=1 TO N+1
460     PRINT Vd(L),Ic(L),Im(L)
470     NEXT L
480   END
490   !
500   !
510   !     ************************************************************
520   !
530   !                                  Subprograms
540   !
550   !                     I_V_char .... Given the operating bias of the MOSBJT
560   !                                   this program calculates the resultant
570   !                                   current and and voltage profile along
580   !                                   the channel and the terminal base and
```

```
590     !                                drain currents.
600     !
610     !                    Wid ...     This subprogram to calculate the average
620     !                                width of a MOSFET circuit element.
630     !
640     !                    Inca ....... This subprogram  calculates the ratio
650     !                                of the collector area of a particular
660     !                                section to the total MOSBJT channel area
670     !
680     !      ******************************************************************
690     !
700     !
710     SUB I_v_char(Vg,Vde,Vbe,INTEGER N,REAL Ic(*),Im(*),Vd(*),Ibi(*),Ibcal)
720     DIM Vs(200)
730     INTEGER Nmin,Nmax,L
740     !
750     GOSUB Modulea
760     GOSUB Moduleb
770     GOSUB Modulec
780     GOSUB Moduled
790     GOTO Fini
800     !
810     !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
820     !                           MODULE A                                  !
830     !                                                                     !
840     !                    1.  Define device parameters                     !
850     !                    2.  Define device geometry                       !
860     !                    3.  Define material constants                    !
870     !                    4.  Define device bias                           !
880     !                    5.  Calculate necessary intermediate parameters  !
890     !                                                                     !
900     !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
910     !
920 Modulea:     !
930     !
940     !         Define device parameters ....
950     !
960     !                   Om - METAL WORK FUNCTION
970     !                   Os - SILICON WORK FUNCTION
980     !                   Eox - PERMETIVITY OF SIO2
990     !                   Es  - PERMETIVITY OF Si
1000    !                   Tox - OXIDE THICKNESS
1010    !                   Qss - SURFACE CHARGE DENSITY
1020    !                   T   - TEMPERATURE
1030    !                   Na - SUBSTRATE DOPING
1040    !
1050    !
1060              Flg=0
1070              Om=4.10                ! V
1080              Os=4.9                 ! V
1090              Eox=3.45E-11           ! F/M
1100              Es=1.04E-10            ! F/M
1110              Tox=1.2E-7             ! METERS
1120              T=300                  ! DEG K
1130              Na=1.5E+16             ! CM ^ -3
1140              Qss=8.E-5              ! C/M^2
1150    !
1160    !
1170    !                   Define device geometry ...
1180    !
```

```
1190  !                                      Length- LENGTH OF GATE
1200  !                                      Width - WIDTH OF GATE
1210  !                                      N     - NUMBER  OF SECTIONS
1220  !
1230  !
1240  !
1250                    Length=3.68E-3       ! METERS
1260                    Width=2.96E-3        ! METERS
1270  !
1280  !
1290  !
1300  !                               Specify BJT parameters ...
1310  !
1320  !                                        AF - FORWARD ALPHA
1330  !                                        AR - REVERSE ALPHA
1340  !                                        IES -
1350  !                                        ICS -
1360  !                                        XB - BASE WIDTH
1370  !
1380                   Af=.962
1390  !                Ar=.998
1400                   Ies=1.04E-8
1410                   Ics=1.002E-8
1420  !
1430  !
1440  !
1450  !                               CALCULATE INTERMEDIATE CONSTANTS
1460  !
1470  !                                       Vfb  -  FLATBAND VOLTAGE
1480  !                                        Vt  - THRESHOLD VOLTAGE
1490  !                                        Dl  - SECTIONAL MOSFET LENGTH
1500  !                                       Cox  - OXIDE CAPACITANCE/AREA
1510  !                                        Mu  - MOBILITY
1520  !                                        Op  - ENERGY DIFFERENCE BETWEEN THE
1530  !                                              INTRINSIC AND EXTRINSIC FERMI
1540  !                                              LEVELS
1550  !
1560  !
1570  !
1580                      Cox=Eox/Tox
1590                      Vfb=Om-Os-Qss/Cox
1600                      Kb=1.38E-23
1610                      Q=1.6E-19
1620                      Mu=.05
1630                      Ni=1.45E+10
1640                      Op=-1*(Kb*T/Q)*LOG(Na/Ni)
1650                      Dl=Length/N
1660                      Vt=Vfb+2*ABS(Op)+(1/Cox)*SQR(2*Es*Q*Na*1.0E+6*(2*ABS(Op)))
1670  !
1680  !        IF THE MOSBJT IS BIASED INTO SATURATION VDE>VG-VT THEN VDE IS SET
1690  !        TO VG-VT
1700  !
1710            IF Vde>Vg-Vt THEN
1720              Vde=Vg-Vt
1730              PRINT "DEVICE SATURATED VDSAT=VG-VT = ",Vde
1740            END IF
1750  !
1760  !
1770  !                                 PRINT THE ABOVE DATA
1780  !
```

```
1790  !
1800          PRINT "OM=",Om
1810          PRINT "OS=",Os
1820          PRINT "EOX=",Eox
1830          PRINT "ES=",Es
1840          PRINT "TOX=",Tox
1850          PRINT "QSS=",Qss
1860          PRINT "T=",T,"K"
1870          PRINT "NA =",Na
1880          PRINT "LENGTH=",Length
1890          PRINT "WIDTH=",Width
1900          PRINT "NUMBER OF SECTIONS IS ",N
1910          PRINT "IES = ",Ies
1920          PRINT "ICS = ",Ics
1930          PRINT "AF = ",Af
1940          PRINT "OP = ",Op
1950          PRINT "VFB = ",Vfb
1960 !
1970 !
1980           RETURN
1990  !
2000  !
2010  !
2020  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
2030  !                                                                    !
2040  !                            MODULE B                                !
2050  !                                                                    !
2060  !                 Determine extent of channel cut-off                !
2070  !                                                                    !
2080  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
2090  !
2100 Moduleb:         !
2110  !
2120  !                       Vbc .. The channel to emitter bias such that Ic=0
2121  !
2130  !                       Vchemim . The channel to emitter bias such that the
2140  !                                 BJT connected to that node Ic is slightly
2150  !                                 greater than 0.  (Node is biased at the
2151  !                                 onset of cutoff)
2152  !
2160  !                       Lco ...   Indicates the current section being
2170  !                                 examined to determine if it is "active"
2180  !
2190  !
2200           Vbc=-(Kb*T/Q)+LOG(Af*Ies/Ics)
2210           Vchemin=Vbc+.01
2220           Vs(1)=Vchemin
2230           Nmin=1
2240           Nmax=N
2250  !
2260 Next_try:   !
2270           Lco=(Nmin+Nmax)/2
2280           Ic(Lco)=0
2290           Im(Lco-1)=0
2300           Vd(Lco)=Vchemin
2310  !
2320  !
2330 Loop1:    !
2340           FOR L=Lco TO N
2350           IF Q*(-Vd(L)+Vbe)/(Kb*T)<-100 THEN GOTO Around1
```

```
2360          Ic(L)=FNInca(Length,Width,N,L)*(Af*Ies*EXP(Q*Vbe/(Kb*T))-Ics*(EXP(
(Q/(Kb*T))*(Vbe-Vd(L)))-1))
2370          GOTO Around2
2380  !
2390 Around1: !
2400          Ic(L)=FNInca(Length,Width,N,L)*Af*Ies*EXP(Q*Vbe/(Kb*T))
2410  !
2420 Around2: !
2430          Im(L)=Im(L-1)+Ic(L)
2440          IF (Vg-Vt+Vd(L))^2-(2*(Vg-Vt)*Vd(L)+Vd(L)^2+(2*Im(L)*Dl)/(Mu*FNWid
(Width,Length,N,L)*Cox))<0 THEN GOTO Cut_off
2450          Vd(L+1)=Vg-Vt+Vd(L)-SQR((Vg-Vt+Vd(L))^2-(2*(Vg-Vt)*Vd(L)+Vd(L)^2+(
2*Im(L)*Dl)/(Mu*FNWid(Width,Length,N,L)*Cox)))
2460          IF Vd(L+1)>Vde THEN GOTO Cut_off
2470          NEXT L
2480 !
2490 !
2500          Nmax=Lco
2510          IF Nmin=Nmax-1 THEN
2520          FOR L=1 TO Lco-1
2530          Ic(L)=0
2540          Im(L-1)=0
2550          Vd(L)=Vchemin
2560          NEXT L
2570          GOTO Found_it
2580          END IF
2590          GOTO Next_try
2600 Cut_off: !
2610          Nmin=Lco
2620          IF (Lco>=N) THEN
2630               DISP " ERROR !!!!!!  ENTIRE CHANNEL IS CUT OFF !"
2640               DISP " RERUN PROGRAM WITH A LARGER N  "
2650               BEEP
2660               PAUSE
2670               END IF
2680          GOTO Next_try
2690  !
2700 Found_it: !
2710           RETURN
2720  !
2730  !
2740  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
2750  !                                                                      !
2760  !                              MODULE C                                !
2770  !                                                                      !
2780  !                        1.  Iterate until Vdcal = Vde                 !
2790  !                        2.  Record the spatial dependence of channel  !
2800  !                            voltage and current                       !
2810  !                                                                      !
2820  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
2830  !
2840 Modulec:      !
2850     K=1
2860 Loop2:   !
2870          FOR L=Lco TO N
2880          IF Q*(Vbe-Vd(L))/(Kb*T)<-100 THEN GOTO Around3
2890          Ic(L)=FNInca(Length,Width,N,L)*(Af*Ies*EXP(Q*Vbe/(Kb*T))-Ics*(EXP(
Q*(-Vd(L)+Vbe)/(Kb*T))-1))
2900          GOTO Around4
2910 Around3: !
```

```
2920            Ic(L)=FNInca(Length,Width,N,L)*(Af*Ies*EXP(Q*Vbe/(Kb*T)))
2930 Around4: !
2940            Im(L)=Im(L-1)+Ic(L)
2950            IF (Vg-Vt+Vd(L))^2-(2*(Vg-Vt)*Vd(L)+Vd(L)^2+(2*Im(L)*Dl)/(Mu*FNWid
(Width,Length,N,L)*Cox))<0 THEN GOTO Decrease
2960            Vd(L+1)=Vg-Vt+Vd(L)-SQR((Vg-Vt+Vd(L))^2-(2*(Vg-Vt)*Vd(L)+Vd(L)^2+(
2*Im(L)*Dl)/(Mu*FNWid(Width,Length,N,L)*Cox)))
2970            IF Vd(L+1)>Vde THEN GOTO Decrease
2980            NEXT L
2990 Adjust:    !
3000 !
3010 !
3020            IF K=1 THEN
3030                Vsmin=Vs(K)
3040                Vsmax=Vs(K)
3050            END IF
3060            IF Flg=1 THEN GOTO Increase
3070            IF Vd(L+1)-Vde>0 THEN
3080            Flg=1
3090            GOTO Decrease
3100            END IF
3110            Vsmin=Vs(K)
3120            Vs(K+1)=SGN(Vd(L+1)-Vde)*(-1.)+Vs(K)
3130            Vd(Lco)=Vs(K+1)
3140            K=K+1
3150            GOTO Loop2
3160 Increase:!
3161            Vdcal=Vd(N+1)
3170            IF ABS(Vdcal-Vde)<.01 THEN GOTO Out
3180            IF SGN(Vdcal-Vde)>0 THEN GOTO Decrease
3190            Vsmin=Vs(K)
3200            GOTO New_guess
3210 Decrease:!
3220            Flg=1
3230            Vsmax=Vs(K)
3240 New_guess:  !
3250            Vs(K+1)=(Vsmax+Vsmin)/2
3260            K=K+1
3270            Vd(Lco)=Vs(K)
3280            GOTO Loop2
3290 Out:                !
3300                     RETURN
3310    !
3320    !
3330    !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
3340    !                                                                 !
3350    !                            MODULE D                             !
3360    !                                                                 !
3370    !                          CALCULATE IB                           !
3380    !                                                                 !
3390    !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
3400    !
3410 Moduled:       !
3420            Ibcal=0
3430            FOR L=1 TO N
3440            IF ((-Vd(L+1)+Vbe)/(Kb*T))<-50 THEN GOTO Around5
3450            Ib=FNInca(Length,Width,N,L)*(Ies*(1-Af)*(EXP(Q*Vbe/(Kb*T))-1)+(Ics
-Af*Ies)*(EXP(Q*(-Vd(L+1)+Vbe)/(Kb*T))-1))
3460            GOTO 3490
3470 Around5:   !
```

```
3480          Ib=FNInca(Length,Width,N,L)*(Ies*(1-Af)*(EXP(Q*Vbe/(Kb*T))-1)-(Ics
-Af*Ies))
3490          Ibi(L)=Ib
3500          Ibcal=Ibcal+Ib
3510          NEXT L
3520          RETURN
3530 !
3540 Fini:              !
3550 !
3560  SUBEND
3570 !
3580 !
3590 !
3600     DEF FNInca(Length,Width,INTEGER N,INTEGER L)
3610     F=N
3620     Inca=1/F
3630     RETURN Inca
3640     FNEND
3650 !
3660     DEF FNWid(Length,Width,INTEGER N,INTEGER L)
3670     Wid=Width
3680     RETURN Wid
3690     FNEND
3700 !
3710 !
```

END

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9-83

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